REPORT DOCUMENTATION PAGE

Form Approved
OPM No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
Report Date

3. REPORT TYPE AND DATES COVERED
Technical

4. TITLE AND SUBTITLE
Pencil Beam Array Development: Final Report

5. FUNDING NUMBERS
ONR Grant #N00014-90-J-1498

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8. PERFORMING ORGANIZATION REPORT NUMBER
None

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
ONR, Code 3210A
Ballston Towers One
800 N. Quincy Street
Arlington, VA 22217-5660

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
distribution statement A. approved for public release. Distribution is unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
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14. SUBJECT TERMS
Subject Terms

15. NUMBER OF PAGES
Pages

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

ONR GRANT #N00014-90-J-1498

PENCIL BEAM ARRAY DEVELOPMENT
Final Report Dec '89 - Mar '94

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ABSTRACT

During FY89 through FY94 we designed and partially constructed a transmit/receive array for imaging the ocean near-surface zone. A planar array of receiving transducers and an end-fire array transmitter. would have produced a shaded transmit beam halfwidth of 30° (3dB), and a receive beam halfwidth of 6° (with shading). Phase delay steering of the receive beam would make it possible to produce images of surface scattering over the region covered by the wider transmit beam. The transmit technology is based on a slotted cylinder transducer produced by Piezo-Sona Tool Corporation that was modified by APL. A series of tests has shown that array source levels in excess of 205dB//μPa at 1m are achievable. Coupled finite-element/boundary-element modeling was used to optimize the design, with an array source level goal of 210dB//μPa at 1m. The end-fire array design used $\lambda/4$ element spacing and 90° phasing to provide at least a 25dB reduction in the back direction. This was important for experiments where the backward beam would cause unacceptable interference. During FY92-93, a proof-of-concept prototype with reduced numbers of transmit and receive elements was designed, fabricated, and tested. Tests were conducted in local waters using a simple, fixed mooring. The final design of the array allowed for pan and tilt, and incorporated features for self-calibration and accurate position measurement. With this array surface, volume, bottom, and ice scattering experiments in both monostatic and bistatic arrangements would have been possible in future measurements. Deployment of the Pencil Beam array system in specific experiments was considered. Funding for this project was terminated in FY93, and work in FY93/94 was focused on the Cascadia Basin Experiment, CABEX. Hardware developed for this project was used in that experiment.

INTRODUCTION

The Pencil Beam array is illustrated in Figure 1. It was to consist of a planar array of receiving transducers and an end-fire array transmitter. As shown in Figure 2, the transmitter would be used to ensonify a large region (shaded beam halfwidth 30°). Receive beamforming (shaded beam halfwidth 6°) and time gating would resolve this region into pixels. The transmitter array was to have 22 elements along its 20 m length ($\lambda/4$ spacing) and be mounted co-axially with the planar receiving array. The receiving array was to consist of 61 elements mounted on a taut circular net, 20 m in diameter. The signal from each receiver element was to be digitized, and centrally recorded for later processing (beamforming and focusing). The array is discussed further subsequently.

In early stages of the ONR Surface Backscatter SRP, we examined the traditional method of using crossed vertical/horizontal line arrays for monostatic/bistatic cross section measurements, and concluded that difficulties involving mechanical stability make them less viable. In addition, the fact that horizontal arrays must be towed at some speed to make them linear poses a serious problem. This gives them only very brief "on station" looks at a desired footprint area. However, in a scientifically controlled experiment, we would have a small surface area that is being carefully characterized environmentally. Thus, we must confine our acoustic measurements to this footprint. For this reason, we felt compelled to propose an array capable of such precise measurements.

For monostatic or bistatic operation, suppression of backlobes through the use of a $\lambda/4$ endfire array with 90° phasing reduces the ambiguity questions that arise from multiple footprint or unwanted bottom/surface ensonification. The very low sidelobes and high source levels would allow us to operate down to low sea states, giving us the ability to test theory and modeling over most scattering conditions.

Development of the complete Pencil Beam array required extensive modeling, design, and testing. At present, the system concept is established, and critical questions regarding transmitting element technology have been answered. In the period FY92-93 we had planned to develop a prototype array intended for proof of concept. This would have allowed tests of many design features; implementation of the full array with mechanical steering was to be completed in the following biennium.

LONG RANGE OBJECTIVES

Our long-range objectives are to understand the basic mechanisms controlling the scattering of sound from the sea surface, the ocean volume, the sea bottom/sub-bottom, and the underice surface. Our emphasis is on stochastic rather than deterministic processes. A related objective is the development of propagation models that are fully consistent with the known physics of the scattering phenomena. The pencil beam transmit/receive array was focused on a capability to make very precise surface/volume/bottom/ice measurements. Ultimately, such measurements would deepen our understanding of the basic mechanisms governing the scattering of sound. The emphasis in the development of the array was on scattering from the sea surface zone.

Another long-range objective was to ensure graduate student (and Post-Doctoral) participation in the development and operation of the array. This participation gives students and post-docs valuable "hands on" experience in an academic research environment. There has been a great tendency in acoustics research to rely on assets owned and operated by the classified elements of Naval laboratories. We believe this tendency has

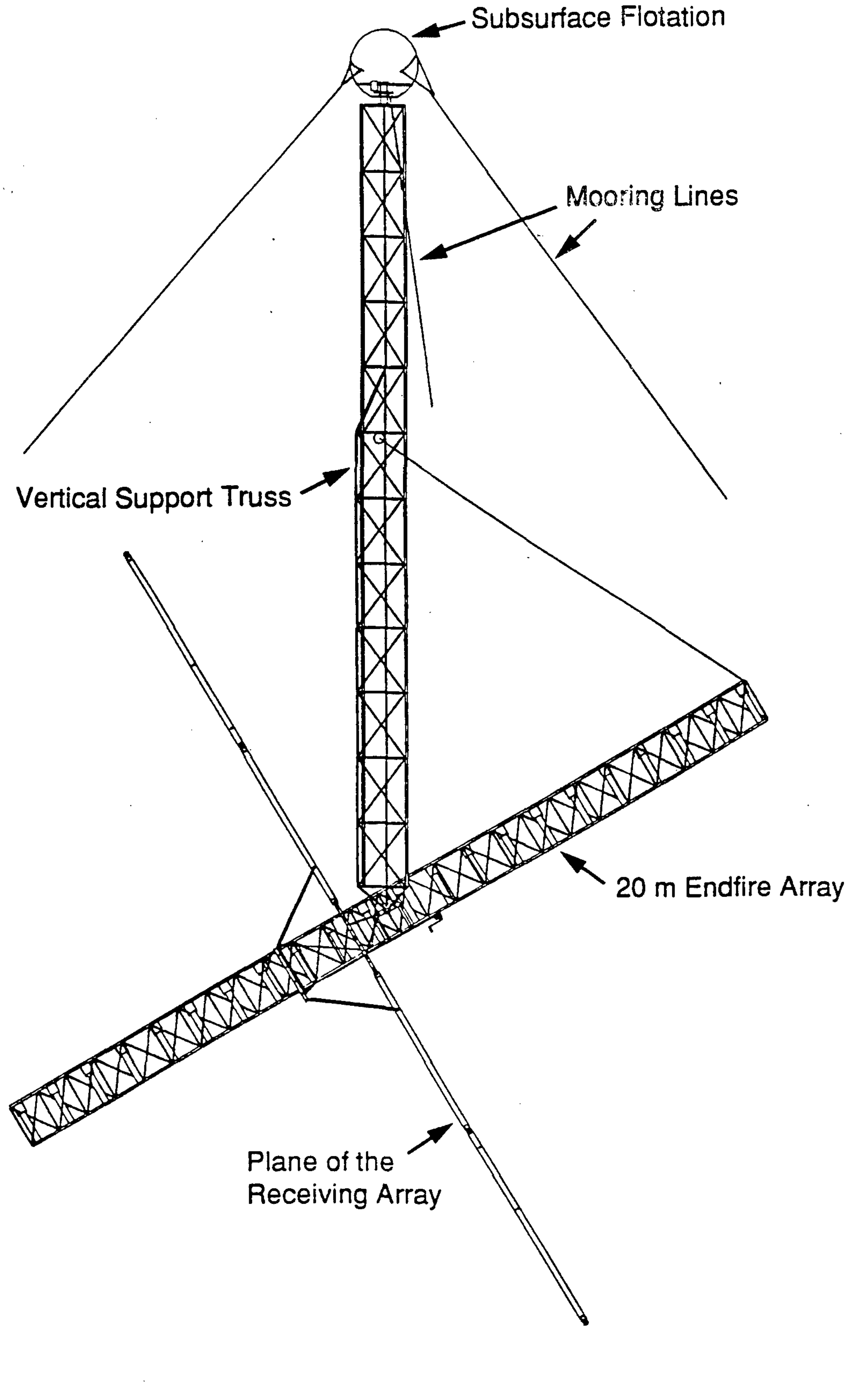

Figure 1. Pencil Beam array for shallow water deployment.

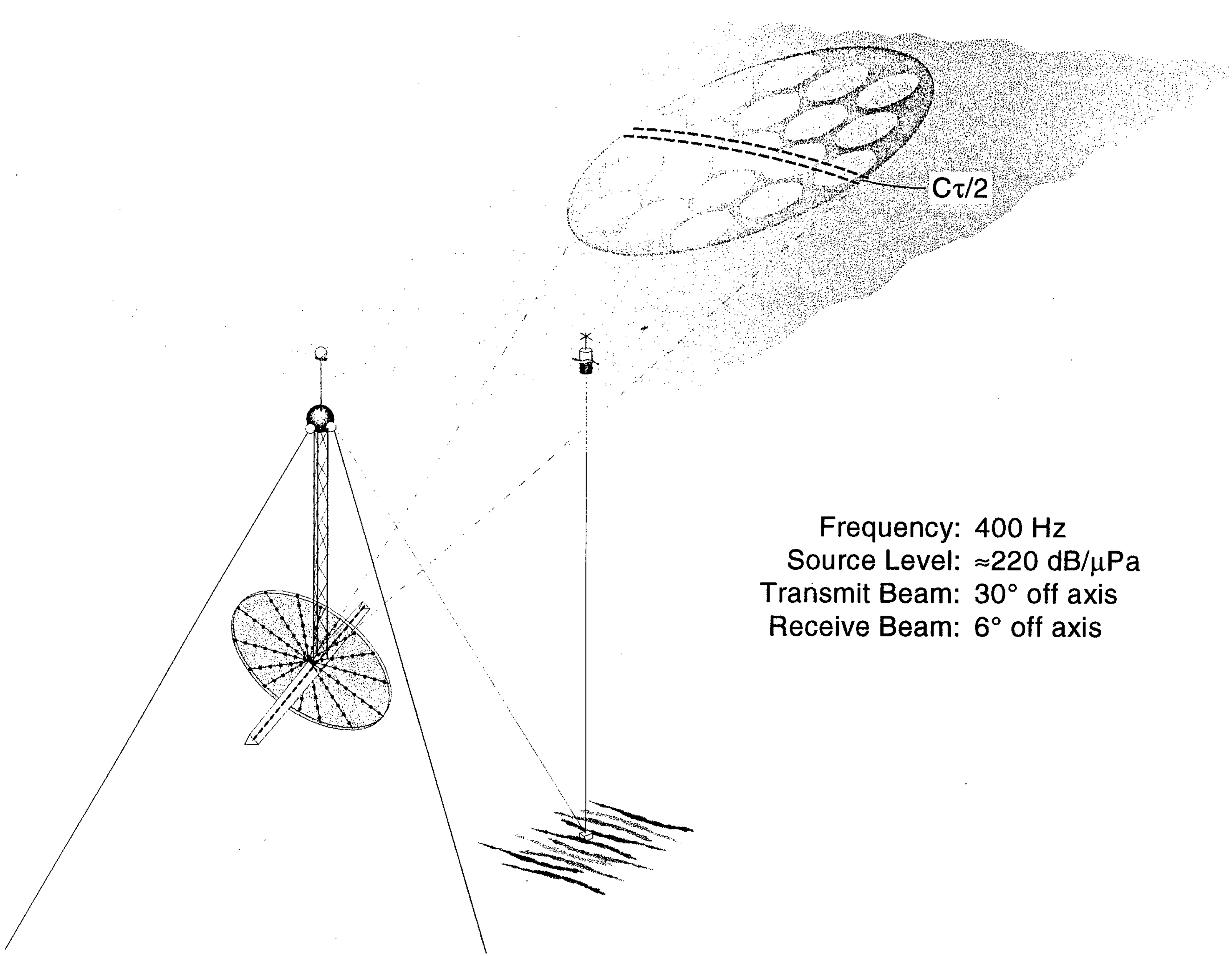

Figure 2. Concept for using the Pencil Beam in a shallow water backscattering experiment.

been deleterious to academic acoustic programs, and ultimately detrimental to the quality of the scientific professionals needed in the discipline of ocean acoustics.

SPECIFIC OBJECTIVES

Our specific objective was to develop and operate the Pencil Beam source/receiver. During FY92, we modeled the acoustic, electronic, and mechanical aspects of the system, and produced an element with $\geq$ 190dB//μPa at 1m that met our bandwidth requirement. During FY93, we had planned to develop a prototype array. That objective was changed to development of the CABEX array under other funding.

BACKGROUND

It has not been possible to test theoretical results for scattering from surfaces with the same precision possible in volume scattering because in the past, the ensonified "footprint" has been poorly characterized. Numerical capabilities in surface scattering have increased to the point where it is known when theory is accurate for some idealized environments (E.I. Thorsos, JASA, **88**, 335, 1990). We forsaw the need to develop a technology that possessed the precision to test whether such theoretical predictions are accurate for ocean scattering, including th effects of near-surface zone bubbles. The pencil beam array was to give us the capability to perform both stochastic and deterministic scattering experiments. This capability could also be exploited in studies of scattering from Arctic ice and from the ocean bottom. The use of the CABEX array in the Arctic during the IBEX experiment demonstrated this very effectively. IBEX was supported by the ONR Arctic program. The directivity and high source level of the Pencil Beam would have opened new possibilities in propagation experiments intended to study volume scattering, and test source and target localization techniques.

Surface Scattering Measurements

The Pencil Beam array was originally conceived for use in experiments supported by the surface component of the ONR Special Research Project in Surface and Bottom Reverberation (SRP). The surface part of the SRP was phased down at the end of FY92. Surface scattering experiments during CABEX were the first application of the pencil beam array technology.

The key scientific question addressed in the surface SRP was whether low grazing angle backscattering at low frequencies becomes enhanced relative to standard theoretical predictions as the sea state rises. Assuming it does, understanding the mechanism(s) responsible for this enhancement becomes an important issue. A third issue is whether scattering from the sea surface, or more generally from the sea surface zone, yields a zero Doppler signature. Our goals in proposed experiments using the array were: (1) to answer the first question conclusively through careful experiments and comparisons with theory, (2) to determine if bubbles or high surface slopes associated with breaking waves or if concentrations of fish are responsible for any enhanced scattering observed, and (3) to attempt Doppler measurements of surface backscattering.

Our approach was to begin experiments at short ranges (< 2 km) using the Pencil Beam array at 400 Hz. The first was to have been conducted in a deep Canadian fjord, with later experiments conducted in the open ocean. Long-range experiments (one convergence zone) were also to have been conducted in the open ocean with the goal of making Doppler measurements and studying other phenomena not accessible in short-range experiments. The high source level ($\geq$ 210dB//μPa at 1m), the narrow beam width of the planar array, and the low side-lobes would be ideal for direct measurements of sea surface scattering cross sections. The use of short ranges minimizes propagation uncertainties and the size of the scattering footprint. A small scattering footprint eases the tasks of environmental characterization and of monitoring the potential for scattering from fish.

In the fjord experiment, the array would have been deployed in relatively shallow water at a depth of 50-100 m. By using a power/data cable to shore, surface vessels would be required only for deployment, retrieval, and possibly for environmental measurements. Thus, backscattering data could be obtained for very rough to very smooth sea states.

Advances in sea surface zone environmental characterization made under the surface SRP was to be utilized in these experiments. Measurements would include 2-D surface wave spectra, white cap coverage, and subsurface bubble densities.

A primary goal of the experiments was to determine the backscattering cross sections per unit area for sea surface layer conditions that range from the classical Dirichlet boundary (presumably at low sea states) to conditions where additional physics is required to explain the observations (presumably higher sea states). This additional physics is expected to arise from near-surface high volume fraction bubble plumes, low volume fraction entrained bubble clouds, non-linear surface wave effects, or other as yet unidentified physical mechanisms. A small subset of these studies was achieved in CABEX.

The Pencil Beam System Instrumentation

Fortunately the apparatus built for the Pencil Beam project was designed in a modular way, so that many experiments could be carried out with the same apparatus. The electronic components have been termed "Acoustic LEGOS," owing to the ease with which varying geometric layouts can be accomplished. It was this flexibility that led to the conduct of CABEX and IBEX with little redesign required.

The Multi-Element Transmitting and Receiving Array

Preliminary design of the array was completed. The proposed transmitting array would have 22 elements in an end-fire configuration with $\lambda/4$ spacing at 400 Hz. The pattern for unshaded operation of this array is shown in Figure 3 (shading increased the beam transmit halfwidth to 30°). The broad transmit pattern provides a wide field of view.

The proposed receiving array had 4 circular distributions of transducers, and a central one, totaling 61 elements. We considered shaded and unshaded patterns for the receiving array. (The product of the unshaded transmit and receive patterns is shown in Figure 3.) The shaded version of the array has a 3dB beamwidth of 6° from axial, the unshaded version has a slightly narrower beamwidth. The end fire transmitting array produces energy in the back direction, at least 25dB below the forward levels. The combined sidelobe and

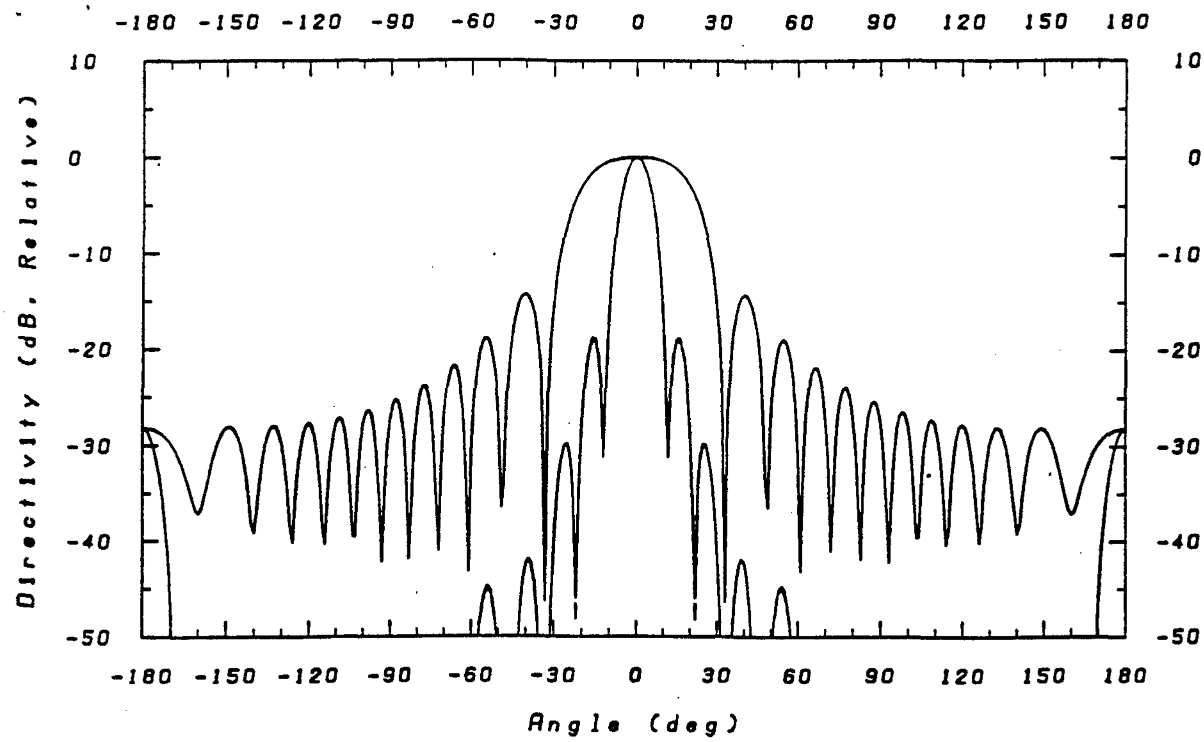

Figure 3. Directivity patterns for unshaded transmit and receive arrays at 400 Hz. The broader curve is the transmitting pattern and the narrower curve is the product pattern for transmit/receive. This pattern can be steered to cover the entire region ensonified by the transmitter. The effect of the proximity of the transmitter elements to the receiver is negligible, as shown by the dashed curve, barely distinguishable from the solid curve.

backlobe levels of the transmitter and receiver would allow very low backscattering cross sections to be measured for monostatic or bistatic scattering from the sea surface, the under-ice surface, or the sea bottom/sub-bottom.

The Transmitting Elements

Development of the sources proceeded along two paths. First, at APL we developed two prototype models based on a design by Ewart and Pence. Tests in FY90 confirmed that source levels of 180-185dB//μPa at 1m were achievable. Second, we purchased standard slotted cylinder transducers from Piezo-Sona Tool Corp (PST). A 750 Hz prototype was loaned to APL by PST in FY90 and evaluated. The evaluation confirmed that the promised specifications had been met, and two 400 Hz units were ordered and delivered in July, 1990. Field testing indicated that a source level of at least 190dB//μPa at 1m should be achievable with this design. Three problems were identified during these tests: (1) pressure-dependent electrical characteristics, (2) in-band parasitic resonances, and (3) narrow bandwidth (the Q was approximately 30).

In consultation with PST, two modified designs were developed. These modifications were based on primitive finite element modeling and were tested in early FY91. Results were favorable, particularly for the simplest design, which employed a rubber boot. Parasitic resonances and depth dependence were suppressed, and the Q was 10, which satisfies the bandwidth requirement for scattering experiments. With this design, a single-element source level of 185dB//μPa at 1m can be achieved with a suitable matching network. Such a design would provide an array source level of 205dB//μPa at 1m, after de-rating for element-element interactions (see following section). Such a source level would satisfy many, but not all, experimental needs.

More detailed modeling with acoustic loading was required in order to optimize the design and to achieve higher source levels. Modeling work in FY90/FY91 employed simplified transducer models and used the GIFTS finite element program. GIFTS does not allow acoustic loading of the model. We switched to the ANSYS finite element code for a more detailed analysis of the transducers. We also investigated codes used by NRL (Orlando), and others, to model transducers, but believed that ANSYS allowed more efficient computation for our problems. Our goal for the optimized design was a single element source level of at least 190dB//μPa at 1m, which would provide an array source level $\geq$ 210dB//μPa at 1m. Subsequently we implemented a boundary element model, SYSNOISE, which operates in conjunction with the ANSYS finite element model to handle the radiation condition. This allowed us to test the element designs for bandwidth, efficiency, and source level. Our final pencil beam transmitter design achieved full agreement between the ANSYS/SYSNOISE modeling, an equivalent circuit model, and the actual measured performance.

Array Element Interactions

The Pencil Beam array used closely-spaced transmitting elements, requiring that the effects of element-element interactions be understood. Element-element interactions within the array have been modeled using a technique originally developed by Pritchard (Pritchard, R.L., JASA **32**, 730, 1960). Accuracy of the method in the domain of interest was verified by measurements made with two elements at variable spacing.

The interaction model (equivalent circuit) showed that, for our end-fire transmitter, interactions do not effect the beam pattern greatly, but result in sizeable self-voltages which limit the array source level to a value about 20dB higher than the single-element

value. (This contrasts to the 26dB maximum theoretical gain.) The model has also been used to estimate the distortion of the receiver pattern due to the proximity of the transmitter elements. This distortion was negligible.

Electronics

A conceptual design for the electronic system was developed during FY90/FY91. Each transmitter element was driven with a separate computer-generated waveform, and the signal from each element of the receiving array was separately digitized for later data processing. Both functions were provided by microprocessor-controlled building blocks. The basic designs of the building blocks ("Acoustic LEGOS") were completed in FY90 and built in early FY91. The building blocks consist of a data concentrator (networked to all of the elements via RS485 protocal), a receiver module, a transmitter module, and a general purpose module. The latter was used, e.g., for reading compass, tilt, and temperature sensors, as well a providing switch control for various functions. Programs for these elements are installed in EPROM memory, but many functions can be changed by downloading instructions from the data concentrator.

The response of each transmitting element was to have been monitored digitally using accelerometers, and the driving waveforms were to be adjusted accordingly. This would permit accurate electronic beam pattern control and allow us to compensate for time-dependent drifts in the electronic component values. A preliminary design of the tuning units and power amplifiers for individual elements was developed in FY90, and built and tested in FY91. The accelerometer feature for control was not incorporated in the CABEX array design.

Beamforming and range gating were to be used to resolve the relatively large footprint of the transmitter into pixels as illustrated in Figure 2. Since the output of each element is recorded, resolution-improving techniques such as superdirective weighting and minimum-variance beamforming could be implemented.

The Mechanical Array And Moorings

Several mooring concepts for the final Pencil Beam array were considered. The most versatile mooring investigated was the pendulum mooring depicted in Fig. 1. This concept would allow the Pencil Beam Array to be steered 360° in azimuth and ±45° in tilt, without mechanical interference or floats in the acoustic pattern.

Launching of this system would be accomplished in stages. In the first stage, the structure was to be deployed horizontally on the surface using auxiliary flotation and a two-point mooring. In this stage, the receiving array would be collapsed onto the endfire transmitter array. In the next stage, the array end of the structure would be partially lowered, and the receiving array would be unfolded.

Once the arrays were unfolded, the support truss would be put in a vertical orientation. At this point, the entire array would be held on location by the two mooring legs. The third anchor line, which also serves as the power/signal cable, would be attached to the support buoy and tensioned to bring the array to operational depth.

Tilting of the array was to be accomplished by using winches to adjust lines attached to each end of the end-fire array structure. Azimuthal steering was to be accomplished by rotating the entire vertical truss with a drive located at the bottom of the support buoy. A high-frequency tracking system would monitor the orientation of the array. Structural members of the trusses would be constructed to the extent possible from thin-

walled tubing, to make them essentially transparent to the 400 Hz acoustic signals.

Although this design has some long structural trusses, no single section would be much larger than the towers used in our 1971 and 1977 acoustic experiments at Cobb Seamount. We would plan to install the moored array during low sea states using diver assistance.

Surface Scattering Modeling

A report (Surface Reverberation Simulations for 400 Hz Arrays, by P.D. Ingalls, APL, May, 1990) was prepared and sent to ONR as part of the ONR-SRP planning process. This report demonstrated the ability of the array to determine low angle backscattering cross sections at low sea states. The following is a summary of some of the important points in that report.

Measurement of small surface scattering cross sections and isolation of point-like events requires that contamination from sidelobe returns be low. Figure 4 shows the results of such a calculation made for the end-fire transmitter and planar array receiver with no shading on the planar array. These calculations assumed a water depth of 400 m, with the array positioned 50 m below the surface and with axis tilted up 10°. Predictions for deeper water can be obtained by scaling, e.g., for 800 m water and 100 m array depth, the same curves apply with a time scale running from 0 to 2 s and with a shift of 12dB in the ordinate. Isovelocity water was assumed. Calculations including moderate refraction do not change the conclusions outlined below.

Figure 4 compares the average surface scattered intensity entering through the main lobe with contaminating intensity arriving from the surface through the sidelobes. If the average intensity received through the sidelobes is comparable to that received via the main lobe, scattering cross sections will be overestimated. A very conservative criterion is that the average intensity received through the sidelobes be at least 20dB below that received through the main lobe. As Figure 4 shows, the sidelobe intensity curve is more than 25dB below the main lobe intensity curve for the unshaded Pencil Beam.

Bottom backscattering is a very strong source of interference in shallow water. Figure 4 shows that the bottom return (entering through sidelobes via direct and surface-bounce paths) is comparable to the main-lobe surface return. In this calculation, rather pessimistic conditions were assumed, with the sidelobe level for the planar array taken to be that of the unshaded array, with the surface scattering strength taken to be small (-60dB at 10° grazing angle) and with the bottom scattering strength taken to be relatively large (-42dB at 10° grazing angle). Under such conditions, surface scattering data can only be obtained in the time interval preceding the direct bottom return. In the fjord experiment, this would provide scattering measurements for grazing angles ≥ 10°. Under slightly more favorable conditions, data can be gathered over longer time intervals, permitting measurement of scattering at smaller grazing angles.

Summary

The pencil beam array design represented a significant advance in acoustic source and array development. The CABEX and IBEX operations, using some of the pencil beam hardware demonstrated that the "Acoustic LEGO" concept worked well, and allowed the scientists to tailor experiments. In IBEX, the electronics demonstrated the capability of

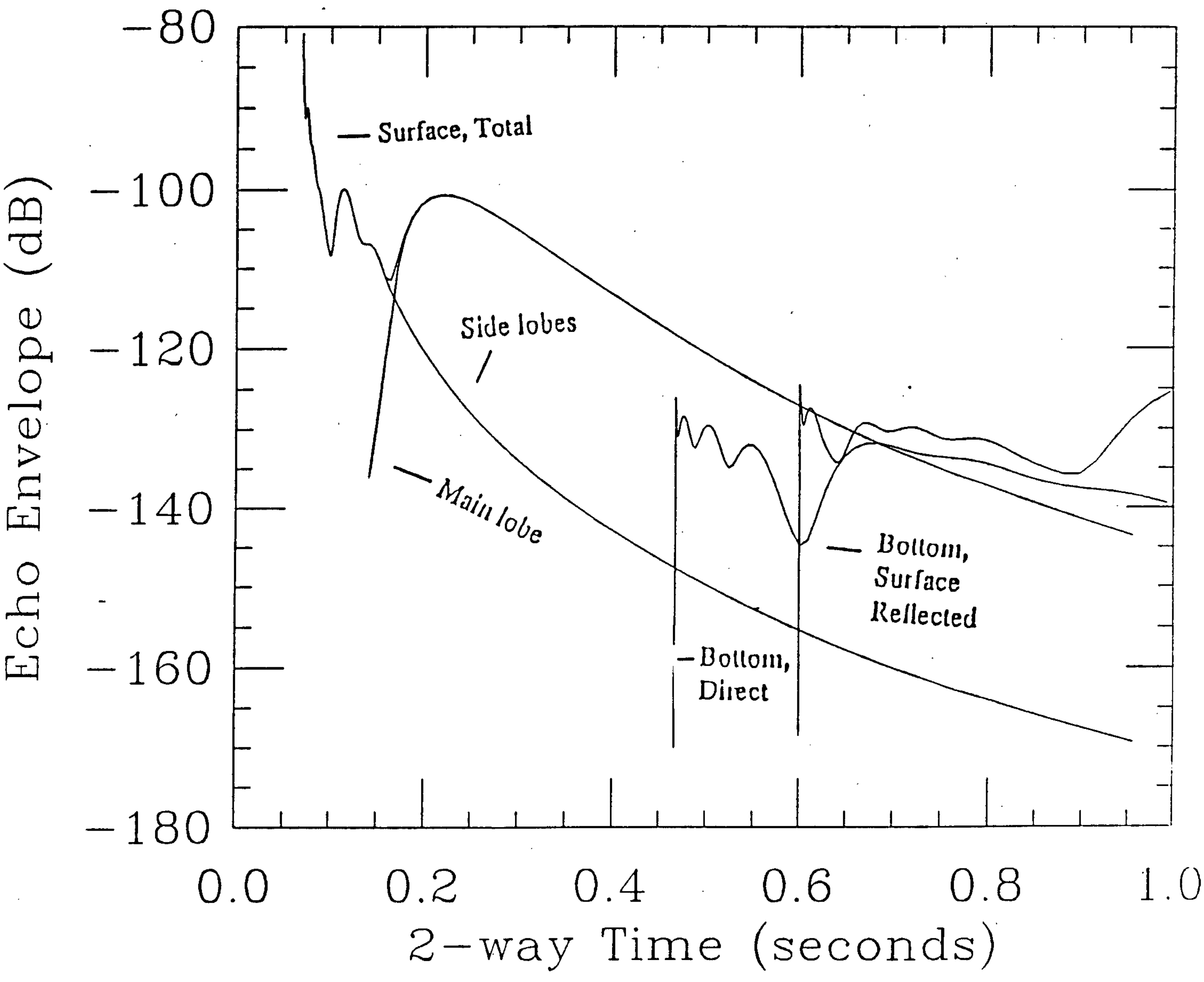

Figure 4. Reverberation levels for the 22 element endfire transmit and 61 element pencil beam receive array.

recording sound levels over 116dB dynamic range. That is 20dB better than your CD player.

FINAL COMMENTS

Certainly the development of the slotted cylinder transmitters was a source of pride to us. Given the funding that the Navy put into slotted cylinder development in classified programs, we demonstrated the possible value of having an academic program linked in to such development. Our sources were built for about $6000.00 each, and were capable of 200dB//μPa at 1m source levels. A lot of ONR money went into this project, and the wasted scientific and engineering time as a result of the cancellation of the project is a good example of how not to do academic science.

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